

# The central elliptical galaxy in fossil groups and formation of BCGs

Habib G. Khosroshahi\*, Trevor. J. Ponman & Laurence R. Jones

*School of Physics and Astronomy, The University of Birmingham, Birmingham B15 2TT, UK*

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## ABSTRACT

We study the dominant central giant elliptical galaxies in “Fossil groups” using deep optical (R-band) and near infrared (Ks-band) photometry. These galaxies are as luminous as the brightest cluster galaxies (BCGs), raising immediate interest in their link to the formation of BCGs and galaxy clusters. However, despite apparent similarities, the dominant fossil galaxies show non-boxy isophotes, in contrast to the most luminous BCGs. This study suggests that the structure of the brightest group galaxies produced in fossil groups are systematically different to the majority of BCGs. If the fossils do indeed form from the merger of major galaxies including late-types within a group, then their disk nature is consistent with the results of recent numerical simulations of semi-analytical models which suggest that gas rich mergers result in disk isophote ellipticals.

We show that fossils form a homogeneous population in which the velocity dispersion of the fossil group is tightly correlated with the luminosity of the dominant elliptical galaxy. This supports the scenario in which the giant elliptical galaxies in fossils can grow to the size and luminosity of BCGs in a group environment. However, the boxy structure of luminous BCGs indicate that they are either not formed as fossils, or have undergone later gas-free mergers within the cluster environment.

**Key words:** galaxies: clusters: general - galaxies: elliptical - galaxies: haloes - intergalactic medium - X-ray: galaxies - X-rays: galaxies: clusters

## 1 INTRODUCTION

It is believed that most of the large and luminous elliptical galaxies have formed via mergers of disk galaxies (Toomre & Toomre 1972; Searle, Sargent & Bagnuolo 1973). This has been suggested by morphology density relation ((Dressler 1980), the observed frequency of merging galaxies at high redshift and also extensively in computer simulations (Barnes 1989). Many of these luminous ellipticals ( $M_B \leq -21$ ) are found in rich galaxy clusters. This, however, does not imply that they are formed in cluster environment. The brightest cluster galaxies (BCGs) are of special interest as they reside close to the centroid of cluster X-ray emission (Jones & Forman 1984), and the centre of the dark matter distribution in clusters, as inferred from gravitational lensing (Smith et al. 2005) – implying that they lie at the minimum of the cluster potential well. They also show various correlations with cluster properties.

In general, two main formation modes could be assumed for the hierarchical formation of BCGs according to their formation environment: **1)** BCGs formed in the high velocity environment of clusters. Although the effectiveness of dynamical friction in bringing individual galaxies to the cluster centre via orbital decay will be reduced by the high velocity dispersion, infalling groups will

still suffer rapid orbital decay if they survive long enough, and can then deposit their brightest galaxies in the cluster core, where they can merge and form a bright elliptical galaxy (Lin & Mohr 2004; Hausman & Ostriker 1978). **2)** BCGs are formed in the low velocity environment of groups, where dynamical friction causes the orbits of individual galaxies to decay, resulting in the merger of all large galaxies, if the group forms early and is left undisturbed for a sufficiently long period (Dubinski 1998; Ponman et al. 1994; Jones et al. 2003). The group containing this ‘ready made’ BCG then provides the nucleus around which a cluster forms.

Elliptical galaxies show fine structures and are more complex than originally thought. These structures take the form of hidden disks, shells and bars, departures from pure elliptical isophotes (Bender 1988) and variations in radial surface brightness profiles (Khosroshahi et al. 2000), some of which are found to be environment dependent (Khosroshahi et al. 2004). BCGs formed in the above two modes should display several observational signatures of how they formed. A useful probe is provided by galaxy morphology – isophotal shapes, radial surface brightness profiles and the presence or not of multiple-nuclei. Different star forming histories are also expected. Some of these studies require space resolution data, but some can be studied using ground based observations, including the isophotes of elliptical galaxies.

Based on their isophotal shapes, elliptical galaxies can be classified as disk or boxy (Bender 1988). Low mass ellipticals,

\* E-mail: [habib@star.sr.bham.ac.uk](mailto:habib@star.sr.bham.ac.uk) (HGK)

which are fast rotating, are usually disk isophote galaxies with positive fourth-order Fourier coefficient  $B_4 > 0$ . Some disk isophote ellipticals might contain faint disks similar to S0 galaxies (Scorza & Bender 1995). With negative  $B_4$ , boxy isophote ellipticals are less rotationally supported. They generally contain flat cores (Faber et al. 1997; Laine et al. 2003) and show complex internal kinematics (Emsellem et al. 2004). The observations of Rest et al. (2001) show that it is very unlikely to find disk ellipticals which are also core galaxies. The majority of the BCGs are found to be core galaxies (Laine et al. 2003). The distinct observed properties of disk and boxy isophotes of elliptical galaxies, such as their radio properties show that they are more than just an artifact of viewing angle or the projection on the plane of sky (Bender 1989).

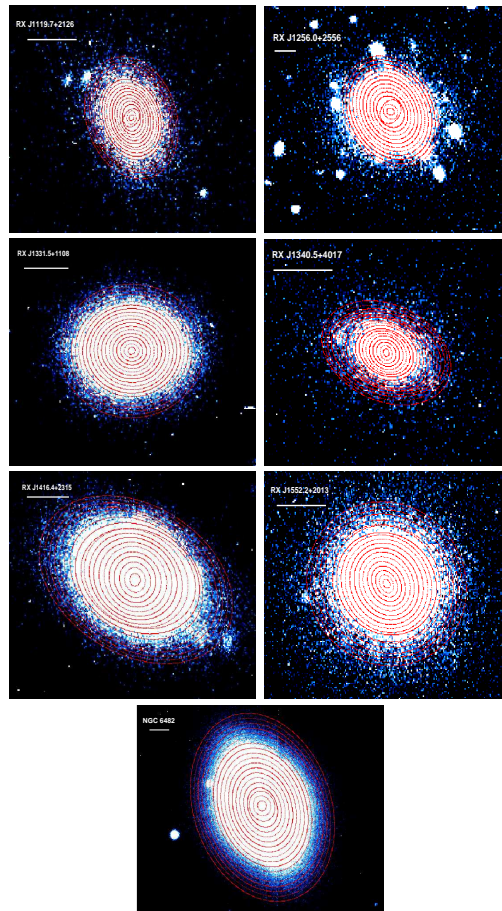
It is important to understand the origin of isophotal shapes before they can be used to trace the formation history of ellipticals. Naab & Burkert (2003) performed a large survey of dissipationless merger simulations of disk galaxies and found that unequal-mass 3:1 to 4:1 mergers lead to fast rotating disk ellipticals while equal-mass 1:1 to 2:1 mergers produce slowly rotating, pressure-supported ellipticals. However, Khochfar & Burkert (2005) showed that the above scenario is not able to reproduce the observation that the fraction of boxy and disk ellipticals depends on galaxy luminosity. They argued that equal-mass mergers lead to boxy ellipticals and unequal-mass mergers produce disk ellipticals. However, major mergers between bulge-dominated galaxies result in boxy ellipticals, independent of the mass ratio, while merger remnants that subsequently accrete gas, leading to a secondary stellar disk with more than 20 per cent of the total stellar fraction, are always disk. More recently they showed that mergers of spiral galaxies alone cannot reproduce the kinematic and photometric properties of very massive elliptical galaxies (Naab, Khochfar & Burkert 2006), nor can they reproduce the observed correlation between isophotal shapes and the luminosity of ellipticals.

Here we study the isophotes of brightest group galaxies (BGGs) in fossils. A brief introduction to fossils is given in section 2 where we also describe the sample and observations. Our analysis and the results are presented in section 3. A discussion and concluding remarks are in section 4. We assume  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $\Omega_m = 0.3$  with cosmological constant  $\Omega_\Lambda = 0.7$  throughout.

## 2 FOSSIL GALAXY GROUPS

In the class of galaxy groups known as “fossil groups”, the group is dominated optically by a single luminous elliptical galaxy at the centre of extended luminous X-ray emission similar to that seen in bright X-ray groups. The X-ray emission in fossils is regular and symmetric, indicating the absence of recent group merging. The dominant giant elliptical galaxy has an optical luminosity similar to BCGs. A cD galaxy has also been reported in a fossil group (Mendes de Oliveira, Cypriano & Sodre Jr. 2005). The observed properties of fossils, and their absence of  $L^*$  galaxies, suggest that they must be old galaxy groups. These properties are discussed in recent studies (Khosroshahi et al. 2006; Khosroshahi, Ponman & Jones 2006) where we report a higher dark matter concentration in fossils, compared to non-fossils groups and clusters with similar masses, which is consistent with an early formation epoch.

Observationally a galaxy group is classified as a fossil if (Jones et al. 2003) it has an X-ray luminosity of  $L_{X, \text{bol}} \geq 10^{42} h_{50}^{-2} \text{ erg s}^{-1}$  spatially extended to few 100 kpc, and the dom-



**Figure 1.** Ellipse fits to the surface brightness distribution of the central galaxy in fossil groups. All the images are from the Ks-band observations with the exception of the most distant fossil, RX J1256.0+2556, which is observed in R-band. 5 arcsec scale bars are also shown.

inant galaxy is at least 2 magnitudes brighter (in R-band) than the second ranked galaxy within half the projected virial radius of the group. The X-ray criterion guarantees the existence of a group size galaxy halo while the optical criterion assures that the  $M^*$  galaxies are absent within the given radius which corresponds to the radius for orbital decay by dynamical friction (Binney & Tremaine 1987). No upper limit is placed on the X-ray luminosity or temperature, and recently a fossil galaxy cluster was found (Khosroshahi et al. 2006).

### 2.1 The sample

This study makes use of a flux-limited sample of fossils found in the catalogue of spatially extended X-ray sources compiled by Wide Angle ROSAT Pointed Survey (WARPS) project. Details of the fossil identification and sample selection is given in Jones et al. (2003). This is the largest statistical sample of fossil groups studied to date. In addition, the nearest known fossil group NGC 6482 and the first discovered fossil group, RX J1340.5+4017, are included in our sample. The detailed X-ray analysis of the sample is the subject of a separate study (Khosroshahi, Ponman & Jones 2006).

## 2.2 Optical and near-IR observations

The above sample was observed using the observational facilities of Issac-Newton Group of Telescopes (ING) and Kitt-peak National Observatory (KPNO). R-band images were obtained using the INT 2.5m wide field imager. Unfortunately the conditions were not photometric, and so further R-band imaging was obtained, in photometric conditions, with the 8k mosaic camera at the University of Hawaii 2.2-m telescope, and in INT wide-field camera service time. The resultant photometric accuracy for all the systems is  $\leq 0.05$  mag. R-band observation of NGC 6482 was performed with the KPNO-0.9m in April 2005. Spectroscopic observations of the sample were also obtained, using slit spectroscopy on the KPNO 4m, to examine the optical membership of these groups. This is discussed in Khosroshahi, Ponman & Jones (2006).

$K_s$ -band observations of the sample using UIST/UKIRT were performed in 2004. The seeing was measured to be  $\sim 1.0''$ . The data were reduced using the ORAC data reduction package (<http://www.oracdr.org/>). Where multi-snaps were taken, the images were co-added to increase the signal-to-noise. Figure 1 shows the  $K_s$  images and their ellipse fits (section 3.3) for the central fossil galaxies in the sample with the exception of RX J1256.0+2556 for which only the R-band data was available.

## 3 ANALYSIS AND RESULTS

Elliptical galaxies are usually single-component galaxies with radial surface brightness profiles described by a de Vaucouleurs law ( $r^{1/4}$ ). It has been shown that the Sersic profile ( $r^{1/n}$ ) gives a better fit, in general, for ellipticals with a wide luminosity range and in different environments (Trujillo et al. 2001; Khosroshahi et al. 2004). Ellipticals are also divided based on their isophotal shapes. For this study we concentrate on the radial surface brightness profile, the ellipticity profile and the fourth order Fourier coefficient ( $B_4$ ), which is an indicator of boxy and disk-like isophotes. The analysis is performed on both the R-band and  $K_s$ -band images using the well-known IRAF/ellipse task.

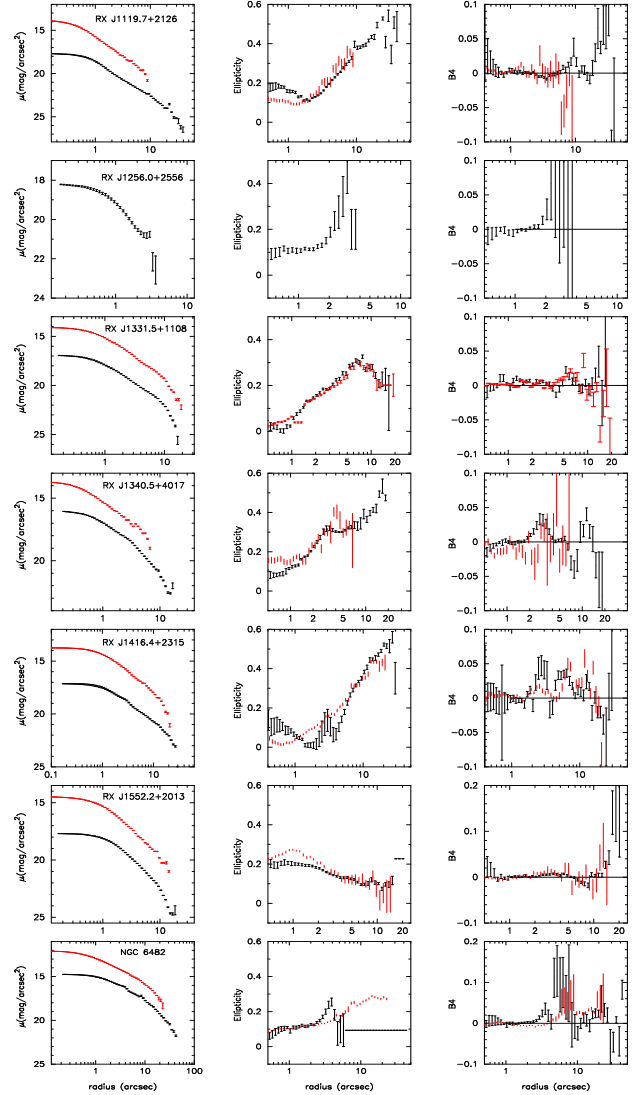
### 3.1 Radial surface brightness profile

The Sersic profile, was used to model the R-band surface brightness distribution of the giant elliptical galaxies, using a two dimensional bulge/disk decomposition method. The values of  $n$  and the half-light radius, along with other parameters, are given in Table 1. The analysis shows that the fossil central galaxies are best modelled with  $\langle n \rangle = 4.1 \pm 0.7$ . While this agrees in general with the surface brightness profiles of the remnants of collisionless disk mergers, these simulations are not able to produce galaxies as large as the dominant fossil galaxies (Naab & Burkert 2003).

Our ground-based observations are inadequate for probing the radial surface brightness profiles within the central  $\sim 1$  kpc, which is necessary for a power-law/core classification. As a result we limit our investigation to the Sersic fit to the galaxy.

### 3.2 Ellipticity profile

The ellipticity profiles presented in Fig 2 show a general pattern in which the ellipticity of the isophotes increases with the radius, with the exception of RX J1552.2+2013. Galaxies with high quality data show ellipticity increasing to 0.4-0.6 exceeding the ellipticity of the X-ray halo which is usually less than 0.3



**Figure 2.** Profiles of radial surface brightness, ellipticity and the fourth Fourier coefficient,  $B_4$ , for RX J1119.7+2126, RX J1256.0+2556, RX J1331.5+1108, RX J1340.5+4017, RX J1416.4+2315, RX J1552.2+2013 and NGC 6482. The profiles extracted from R-band and  $K_s$ -band data are shown in dark (black) and grey (red), respectively.

(Buote & Canizares 1996). The central galaxy in fossils are aligned with the underlying dark matter confirmed both in X-ray and lensing studies. Similar alignment has been noted for the BCGs in many clusters (Fuller, West & Bridges 1999).

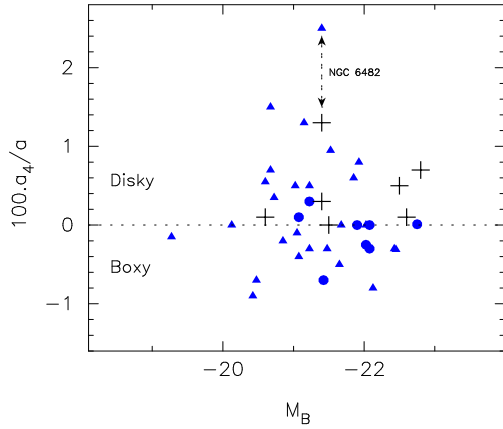
### 3.3 Isophotal analysis

Fig 2 shows the results of the ellipse fits. In order to quantify the shape of the isophotes and to be able to make a direct comparison with similar analyses in the literature, we calculate  $a_4/a$ , which is based on the measured fourth Fourier coefficient,  $B_4$  (Jorgensen et al. 1999). Similarly to Bender (1989),  $a_4/a = \frac{\sqrt{1-\epsilon}B_4}{adI/da}$  is quantified at its peak value. In the absence of a peak the  $a_4/a$  is quantified at  $r_e$ . Here  $\epsilon$ ,  $a$  and  $I$  are the ellipticity, semi-major axis length and the surface brightness of the isophotes, respectively. As seen in Fig.2 none of the galaxies have predomi-

**Table 1.** Photometric properties of the sample galaxies.

Group	R.A. (J2000)	Dec. (J2000)	$z$	$M_R$ mag	$a_4/a$ $\times 100$	$n$	$r_e$ arcsec	kpc/arcsec
RX J1119.7+2126	11:19:43.6	+21:26:51	0.061	-22.1	0.1	5.1	8.9	1.14
RX J1256.0+2556	12:56:03.4	+25:56:48	0.232	-24.1	0.1	3.1	7.3	3.73
RX J1331.5+1108	13:31:30.2	+11:08:04	0.081	-22.9	0.3	4.3	7.2	1.53
RX J1340.5+4017 <sup>a</sup>	13:40:33.4	+40:17:48	0.171	-23.0	irr	4.2	7.6	2.92
RX J1416.4+2315	14:16:26.9	+23:15:32	0.137	-24.3	0.7	3.6	12.1	2.44
RX J1552.2+2013	15:52:12.5	+20:13:32	0.135	-24.0	0.5	4.6	15.8	2.40
NGC 6482 <sup>b</sup>	15:52:12.5	+20:13:32	0.013	-22.9	1.3	3.8	16.0	0.26

<sup>a</sup> This system is the first confirmed fossil group and not part of the flux-limited sample of fossils. <sup>b</sup> This group is known to be the nearest fossil system (Khosroshahi, Jones & Ponman 2004) and is not part of the flux-limited sample.



**Figure 3.** The variation in isophotal shapes of early-type brightest group or cluster galaxies, and those in fossil groups (crosses), with the optical luminosity of the brightest galaxy. The comparison sample is a combination of early-type BGGs (triangles) and BCGs (circles) from Ellis & O’Sullivan (2006), for which  $a_4/a$  values were available.

nantly boxy isophotes, except in the outskirts where the statistics are very poor and the values of  $B_4$  are not well constrained.

We compare the values of  $a_4/a$  with those of the brightest galaxies in groups and clusters, BGGs and BCGs (Fig 3). It is clear from this plot that none of the fossil’s dominant galaxies have prominent boxy isophotes. Indeed some, including the nearest fossil, NGC 6482 (Khosroshahi, Jones & Ponman 2004), and the fossil cluster, RX J1416.4+2315 (Khosroshahi et al. 2006), are highly disk isophote galaxies. An earlier study (Faber et al. 1997) gives an even higher value for the diskyness of NGC 6482. The comparison sample is a combination of early-type BGGs and BCGs from Ellis & O’Sullivan (2006) for which  $a_4/a$  values were available from earlier studies and therefore it is not a complete sample.

#### 4 DISCUSSION AND CONCLUSIONS

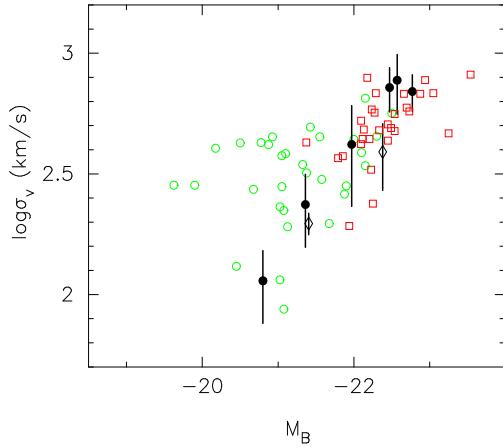
This analysis shows that, despite apparent similarities, the dominant giant elliptical galaxy in fossil groups are different in their isophotal shapes, compared to the brightest central galaxies in non-fossil systems, especially in rich clusters. Luminous elliptical galaxies in non-fossil groups and clusters do not present disk isophotes. Less luminous BGGs show disk and boxy isophotes in similar proportions. However, the observed frequency of boxy-isophote dominant fossil galaxies is apparently zero.

If the central galaxies of fossil groups have indeed been formed from the merger of all major galaxies within the inner regions of the group, as we suppose, then some of these mergers would have been gas-rich, as group spirals are incorporated into the central merger-remnant. The disk character of central fossil galaxies is then consistent with the findings of numerical simulations, that disk isophotes result from gas rich mergers. Khochfar & Burkert (2005) highlight the importance of the role of gas in galaxy mergers and show that the isophotal shapes of merger remnants are sensitive to the morphology of their progenitors and to subsequent gas infall. In contrast, boxy isophote ellipticals are formed by equal-mass mergers of bulge dominated galaxies. Such mergers are likely to occur at the core of clusters where most of the galaxies are gas poor.

Almost 90% of BCGs studied by Laine et al. (2003) are core galaxies, i.e. with flatter slope near the nucleus in their radial surface brightness profiles. The study by Faber et al. (1997) shows that a large fraction ( $\sim 70\%$ ) of core galaxies have boxy isophotes, with as low as  $\sim 10\%$  with disk isophotes, implying a strong association of boxy isophotes with core galaxies. Taking into account the conversion of cuspy cores into flat low-density cores by black hole merging, Khochfar & Burkert (2005) find that disk ellipticals should contain central density cusps whereas boxy ellipticals should in general be characterised by flat cores. Only rare low-luminosity boxy ellipticals, resulting from equal-mass mergers of disk galaxies, could have power-law cores. Space resolution data is needed to study the core of the galaxies to verify the core and power-law property of dominant fossil galaxies. If future observations show that fossil group dominant galaxies are power-law galaxies, as expected from their isophotes in light of the above argument, then they will be the first of such entities to grow to the size of BCGs.

The link between fossil galaxy groups and the BCGs is further motivated by observational space density estimates of fossils which is found to be 8% to 20% of X-ray luminous systems (Jones et al. 2003) and as large as the space density of poor and rich galaxy clusters combined. This means that there are enough fossils to provide BCGs to clusters. A recent theoretical study (Milosavljevic et al. 2006) predicts 5%-40% of galaxy groups and 1%-3% of galaxy clusters to be fossils. In the context of BCG formation, fossils appear to be suitable environments for the formation of luminous giant ellipticals around which clusters can form. This is a different formation mode to the one in which the BCG forms via mergers of brightest group galaxies during the cluster collapse. Numerical simulations suggest that the isophotes of the BCGs formed in the latter case will be predominantly boxy, characteristic of gas free (“dry”) mergers.





**Figure 4.** A comparison between the correlation of group/cluster velocity dispersion and absolute B-magnitude of the dominant galaxy. The data points from Table 1 (except RX J1119.7+2126) are shown with filled circles. Diamonds represent two of the fossil candidate OLEGs, out of four, in Yoshioka et al. (2004). The correlation is much tighter in fossils than in non-fossil groups (circles) and clusters (squares). The comparison non-fossil groups are GEMS X-ray selected groups with early-type BGG and with group scale X-ray emission (G-sample in Osmond & Ponman (2004)). The cluster sample is selected from Girardi et al. (2002) for which the luminosity of the central galaxy was available in Lin & Mohr (2004).

The BGGs and BCGs with non-boxy isophotes in Fig.3 could easily originate as fossil group central galaxies which have been incorporated into larger structures. The difference in photometric structure seen clearly in many BCGs and BGGs, especially the most luminous ones, does not rule out the possibility that they originated in fossil groups. This could still be the case provided that they have undergone later gas-free mergers within the cluster environment – for example, with the BGGs of infalling galaxy groups. About 40% of BCGs contain at least one secondary nucleus (Laine et al. 2003), which strongly suggests the action of late mergers within the cluster environment. If fossils are indeed old and undisturbed systems then they should be found to have a very *low* incidence of multiple nuclei.

In support of the above argument we show (Fig 4) a tight correlation between the luminosity of the central galaxy in fossils and the underlying gravitational mass probed by the group velocity dispersion. This shows that fossils form a homogeneous population in which the luminosity of the central galaxy is strongly tied to the property of its parent group. This property of the fossils is consistent with their early formation epoch and absence of recent merger. In contrast the large scatter in the distribution of the non-fossil galaxy groups and clusters, on the same plane, is understood to be merger driven. Absence of a recent major merger helps the dominant fossil galaxy preserve its original structure.

We conclude that there is high chance that disk BCGs are formed in fossil groups. Boxy BCGs, could still result from progenitor fossils, but would need to have undergone a dry merger within the cluster, probably as a result of merger with BGGs of infalling groups.

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